Repair of Conotruncal Abnormalities With the Use of the Valved Conduit: Improved Early and Midterm Results With the Cryopreserved Homograft

JEFFREY M. PEARL, MD, HILLEL LAKS, MD, FACC,
DAVIS C. DRINKWATER, JR., MD, FACC, DANA K. LOO, BS,
BARBARA L. GEORGE, MD, FACC, ROBERTA G. WILLIAMS, MD, FACC
Los Angeles, California

Repair of complex cardiac lesions has been facilitated by the availability of valved conduits to reestablish right ventricular to pulmonary artery continuity. From 1977 to June 1991, 148 patients underwent repair with insertion of a conduit. Their mean age was 6.6 years (11 days to 45 years). The diagnosis was transposition of the great arteries with ventricular septal defect and left ventricular outflow tract obstruction in 51, truncus arteriosus in 36, pulmonary atresia with ventricular septal defect in 25, tetralogy of Fallot in 19, double-outlet right ventricle in 10, pulmonary atresia with intact ventricular septum in 6 and atrioventricular canal with pulmonary atresia in 1.

A Dacron porcine-valved conduit was used in 37, a homograft conduit in 106 and a nonvalved conduit in 5. There were 13 early deaths overall (8.8%); 8 (22%) of the early deaths occurred in the 37 patients who received a Dacron graft, 4 (3.8%) occurred in the 106 patients who received a homograft and 1 occurred in a patient with a nonvalved Gore-Tex conduit. An additional patient underwent orthotopic heart transplantation in the early postoperative period. In 117 patients operated on from January 1985 to June 1991 the early mortality rate was 2.6% (3 of 117). Among 28 patients receiving a Dacron porcine-valved graft there were two late deaths (7.1%) after a mean follow-up interval of 93 months, and 8 patients required reoperation for conduit obstruction. Among 102 homograft recipients there were two late deaths (1.9%). Six homografts (5.9%) have required replacement for stenosis during a mean follow-up interval of 50 months.

The use of a cryopreserved homograft has been associated with a reduced early mortality and excellent early and midterm results for repair of conotruncal abnormalities.

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The use of extracardiac conduits has greatly advanced the surgical management of many types of congenital heart defects. The extracardiac conduit is most frequently used to establish continuity between the right ventricle and the pulmonary artery as part of the anatomic repair in many conditions. These include pulmonary atresia, tetralogy of Fallot with either severe outflow tract obstruction or anomalous origin of the left anterior descending coronary artery, truncus arteriosus and complex forms of transposition of the great arteries (1–7). Physiologic repair is now possible for many of these congenital defects. With a reduction in early mortality, attention has turned to the long-term outcome in patients with such repair, particularly the long-term function of the variety of valved conduits used.

Review of late results from many centers (8–17) reveals the development of conduit obstruction and valve failure requiring reoperation in a significant number of patients (10% to 50% at 5 years). Long-term patency has varied in the many types of conduits and valves tried. With development of techniques of cryopreservation, the homograft has been reintroduced and advocated as a superior conduit with improved long-term function over that of a porcine-valved conduit. In this report we review our experience with the surgical repair of conotruncal abnormalities with the use of a valved conduit. The effectiveness of this form of surgical management, as well as the long-term outcome of the various conduits, is discussed.

Methods

Patient profile. From 1977 to June 1991, 148 patients underwent repair of complex congenital cardiac lesions with the use of a valved or nonvalved conduit from the right ventricle to the pulmonary artery. Because the physiology and anatomy of lesions requiring a Fontan procedure and the resultant flow dynamics are different, patients with a Fontan repair were not included in this series. The diagnoses included transposition of the great arteries with ventricular septal defect and left ventricular outflow tract obstruction in 51 patients, truncus arteriosus in 36, pulmonary atresia with

From the Division of Cardiothoracic Surgery, Department of Surgery and the Division of Pediatric Cardiology, University of California, Los Angeles Medical Center, Los Angeles, California.

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Address for correspondence: Hillel Laks, MD, Division of Cardiothoracic Surgery, UCLA Medical Center CHS 62-182, 10833 LeConte Avenue, Los Angeles, California 90024.

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ventricular septal defect in 25, complex forms of tetrology of Fallot in 19, double-outlet right ventricle in 10, pulmonary atresia with intact ventricular septum in 6 and an atrioventricular (AV) canal in 1 patient. The mean age was 6.6 years (range 11 days to 45 years). Twenty-nine patients were <1 year old at the time of operation; 62 patients were male and 86 female. Twenty-one operations were reoperations for a failed conduit.

A Dacron porcine-valved conduit was used in 37 patients, a homograft conduit in 106 and a nonvalved conduit in 5. The nonvalved conduits included two nonvalved Dacron conduits, one pericardial tube and two Gore-Tex conduits. The average homograft size was 15 mm (11 to 25 mm) and the average Dacron conduit size was 17.5 mm (12 to 25 mm). Of the homografts used, 84 were aortic and 22 were pulmonary. Glutaraldehyde-treated pericardium (n = 19) or, more recently, albumin-impregnated Dacron (n = 65) was used for proximal augmentation.

Patient selection. Patients requiring valved conduit placement were selected according to established criteria. Pulmonary vascular resistance, ventricular function and pulmonary artery anatomy were key factors in determining suitable operative candidates and in planning the operative approach. The decision regarding conduit type and size was made at the time of operation by the attending surgeon on the basis of patient age and size, specific lesion and conduit availability. In the more recent cases homograft conduits with Dacron augmentation were used preferentially. Inclusion in the study was voluntary and follow-up was kept confidential.

Surgical technique. Patients were placed on cardiopulmonary bypass with bicaval cannulation (DLP). A left ventricular vent (DLP) was placed through the right superior pulmonary vein in most cases. After cooling to 24°C, the heart was arrested with warm, substrate-enriched blood cardioplegic solution followed by a multidose cold blood cardioplegic solution. More recently cardioplegic solution was delivered retrograde through the coronary sinus, particularly when aortic or truncal valve regurgitation was present. Topical hypothermia was also employed.

A ventriculotomy was made in the right ventricular outflow tract (Fig. 1A) and the ventricular septal defect, when present, was closed either primarily or with a Dacron patch (Fig. 1B). Pulmonary artery reconstruction was performed when necessary with use of pericardium, homograft or polytetrafluoroethylene. The distal conduit anastomosis was performed first with a running polypropylene suture reinforced with a pericardial strip. The proximal anastomosis was then completed with a running polypropylene suture reinforced with two strips of pericardium (Fig. 1, B and C). When a homograft conduit with proximal Dacron augmentation was used, the graft was constructed with the technique described by Bailey et al. (18); the Dacron tube is scalloped to accommodate the sinuses of the homograft valve root. When a stenosis was present at the pulmonary artery bifurcation, a pulmonary homograft that contained its native bifurcation was used for reconstruction, augmented by pericardium when necessary.

After the patient was removed from cardiopulmonary bypass, the anastomoses were checked for bleeding. Thrombin-soaked Gelfoam or cryoprecipitate-thrombin glue, or both, was used to control significant bleeding from stitches. Right atrial and left atrial pressure lines were placed, as well as epicardial pacing wires. The chest was closed with attention given to positioning of the conduit to avoid sternal compression. A piece of Marlex or Dacron mesh or, more recently, Gore-Tex membrane, was placed underneath the sternum to protect the conduit should reoperation be necessary. In seven patients sternal closure was not tolerated and the chest was left open during the early postoperative period.

Follow-up. Early mortality included all deaths occurring within 30 days of operation, as well as all hospital deaths. Long-term follow-up was obtained from review of clinic records, conversation with the referring pediatric cardiologist and direct contact with the patient and family. Available postoperative echocardiographic or catheterization data were obtained, and all patients were assigned a New York Heart Association functional class.

Results

Early outcome (Table 1). The early mortality rate was 8.8% overall (13 of 148). It was 22% (8 of 37) in patients with a Dacron conduit compared with only 3.8% (4 of 106) in those with a homograft. An additional early death occurred in the one patient who received a nonvalved Gore-Tex conduit. The early mortality rate in the later years of the study (from 1985 to June 1991) was only 3.4% (3 of 117). The early mortality rate was relatively higher for patients undergoing conduit placement for both truncus arteriosus (16.7%) and pulmonary atresia with ventricular septal defect (12%); it was low (3.9%) in the group with complex transposition of the great arteries. There were two intraoperative deaths. Two deaths were secondary to tamponade: one presumably from bleeding from stitches in a Dacron conduit and the other from sudden conduit bleeding in a homograft recipient with suprasystemic right ventricular pressure. Two deaths occurred secondary to respiratory failure and seven deaths secondary to primary myocardial failure with subsequent multisystem failure. An additional patient with complex transposition of the great arteries underwent successful orthotopic heart transplantation performed 4 days postoperatively because of myocardial failure.

One early death occurred in a 14-month old boy with tetralogy of Fallot who underwent attempted tetrology repair but was unable to undergo right ventricular outflow tract patching because of a coronary artery anomaly. He was returned to the operating room for placement of a 16-mm porcine-valved Dacron conduit the following day and died postoperatively from myocardial failure despite support with an intraaortic balloon pump. A second early death occurred

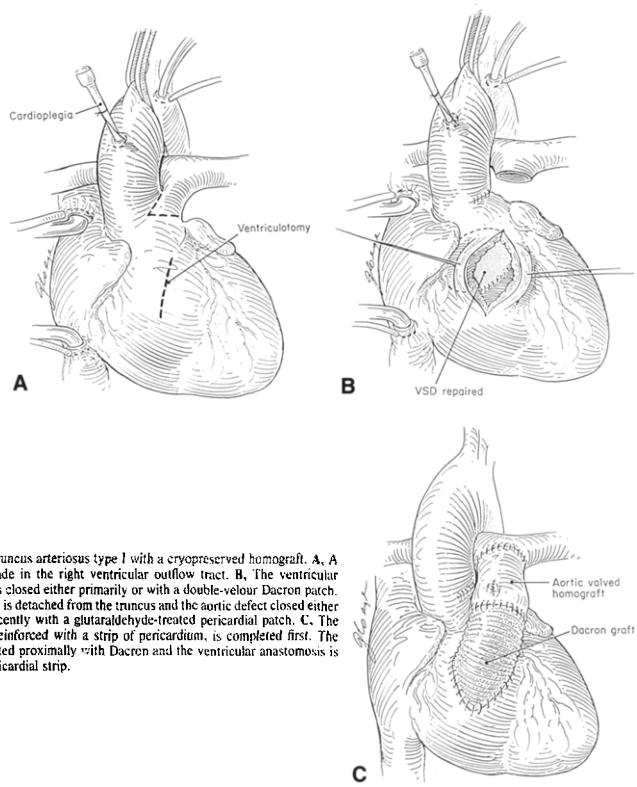

Figure 1. Repair of truncus arteriosus type I with a cryopreserved homograft. **A**, A ventriculotomy is made in the right ventricular outflow tract. **B**, The ventricular septal defect (VSD) is closed either primarily or with a double-velour Dacron patch. The pulmonary artery is detached from the truncus and the aortic defect closed either primarily or more recently with a glutaraldehyde-treated pericardial patch. **C**, The distal anastomosis, reinforced with a strip of pericardium, is completed first. The homograft is augmented proximally with Dacron and the ventricular anastomosis is reinforced with a pericardial strip.

in an 11-day old infant with truncus arteriosus type II and interrupted aortic arch who underwent repair with placement of a 13-mm homograft. The infant was critically ill preoperatively and had a cardiopulmonary arrest in the operating room before operation. He was resuscitated and underwent homograft placement; he died 2 days postoperatively from primary myocardial failure. One death occurred in a 2-month old patient with truncus arteriosus type I who underwent placement of a 12-mm homograft and died on postoperative day 1 from respiratory arrest secondary to dislodgment of the endotracheal tube (Table 1).

Late outcome (Table 2). Long-term follow-up of 135 patients (average 57 months, range 2 to 177 months) showed a late mortality rate of only 3%. The late mortality rate was 7.1% in the group with a Dacron porcine-valved conduit. One late death in this group occurred on postoperative day 1 after repeat operation in a patient with pulmonary atresia and ventricular septal defect who required replacement of a Dacron conduit 11 months postoperatively secondary to critical conduit stenosis. Eight of the 28 Dacron conduit recipients followed up required conduit replacement for obstruction during a mean follow-up interval of 78 months

Table 1. Summary of 13 Early Deaths (8.8%) in 148 Patients Undergoing Conduit Placement

Diagnosis	Pt Age	Conduit	Days From Op to Death	Cause of Death
TA	3.5 yr	Dacron	1	Tamponade
TA	4 mo	Dacron	7	Respiratory arrest
TA	11 days	Homograft	2	Myocardial failure
TA	2 mo	Homograft	1	Pulm/CV failure
TA	6 yr	Gore-Tex/Dacron	28	Myocardial failure
TA	6 wk	Homograft	1	Tamponade/myocardial failure
PA-VSD	6 yr	Dacron	1	Myocardial failure
PA-VSD	4 yr	Dacron	O.R.	—
PA-VSD	14 yr	Dacron	3	RV conduit leak
PA-IVS	7 mo	Dacron	1	Myocardial failure
Complex TGA	7 yr	Dacron	11	Myocardial failure
Complex TGA	15 yr	Dacron	O.R.	—
ToF	2 yr	Homograft	3	Myocardial failure

Op = operation; O.R. = operating room; PA-IVS = pulmonary atresia and intact ventricular septum; PA-VSD = pulmonary atresia with ventricular septal defect; Pt = patient; Pulm/CV = pulmonary/cardiovascular; RV = right ventricular; TA = truncus arteriosus; TGA = transposition of the great arteries; ToF = tetralogy of Fallot.

(28.6% replacement rate at 93 months). The earliest replacement of a Dacron conduit occurred 11 months postoperatively. Current evaluation of the remaining Dacron conduits reveals progressive peel formation in seven and valvular stenosis and degeneration with significant regurgitation in five, with the incidence more prevalent in the older conduits. One of the two patients with a nonvalved Dacron conduit required placement of a porcine valve 9 months postoperatively because of valve regurgitation. Both of these two patients are currently doing well.

The homograft conduit group had a late mortality rate of 1.9%. In 102 patients followed up a mean of 50 months six homografts required replacement because of obstruction. A localized fibrous stenosis that was probably technical in nature developed in one homograft. The lesion was successfully dilated by balloon angioplasty on two separate occasions with good functional results; the first dilation reduced a 50-mm Hg gradient to 20 mm Hg, and the second reduced a 40-mm Hg gradient to 20 mm Hg. One late death occurred secondary to right ventricular failure in a homograft recipient 6 months after repair of tetralogy of Fallot. A second late death occurred secondary to left ventricular failure 5 months postoperatively in a patient with truncus arteriosus.

On follow-up, the majority of homograft conduits had calcification of the conduit wall, but relatively few manifested valve leaflet calcification. Available catheterization and echocardiographic data revealed five mild gradients of 10 to 22 mm Hg in five patients, all with complex transposition of the great arteries. The site of stenosis in the homografts was usually in the distal portion of the conduit.

Table 2. Comparison of Mortality Rate and Replacement Rate of the Dacron Conduit Versus the Homograft in 135 Patients

	Dacron	Homograft	Overall
Early mortality (%)	22	3.8	8.8
Late mortality (%)	7.1	1.9	3
Replacement (%)	28.6	5.9	10.4
Follow-up (mo)			
Mean	93	50	57
Range	11–177	2–75	(2–177)

Discussion

Early outcome. Before the development of an adequate replacement conduit, complex cardiac lesions requiring creation of a connection between the right ventricle and pulmonary artery could not be corrected. The introduction of the valved conduit has greatly facilitated the surgical repair of these various lesions whose basic defect is right ventricular to pulmonary artery discontinuity (conotruncal abnormalities) (1–3). The operative mortality rate has gradually decreased with improvement in myocardial protection, surgical technique and conduit design and availability. The early mortality rate in our series (8.8%) compares quite favorably with that of other series (10% to 35%) (9–12,16,17,19).

In our more recent experience utilizing the cryopreserved homograft, the early mortality rate decreased to 3.8% (4 of 106), indicating an apparent benefit with respect to early mortality with use of the cryopreserved homograft (3.8%) rather than the Dacron porcine-valved conduit (22%). The early mortality rate with the Dacron porcine-valved conduit is comparable to that reported by the group (16) at Boston Children's Hospital (22%). Although the cryopreserved homograft was used later in our experience than the Dacron porcine-valved conduit, our impression is that the superior hemostatic properties, ease of insertion and decreased risk of early obstruction of the homograft are also responsible for these improved results.

Early mortality was relatively higher for patients undergoing conduit placement for truncus arteriosus or pulmonary atresia with ventricular septal defect than for other patient

groups. This finding is similar to that of many other series and in the case of truncus arteriosus may be due to the young age and poor preoperative status of the patients, as exemplified by the 1- and 2-month old patients with truncus arteriosus and interrupted aortic arch in our series.

Of interest is the low operative mortality (3.9%) in the group with complex transposition of the great arteries in our series. Reports from other surgical units (1,6,18–20) indicate difficulty with conduit placement and sternal compression in this group, which has resulted in a higher early mortality and a higher incidence of early conduit stenosis. In patients with transposition and left ventricular outflow tract obstruction there is a tendency to place the conduit to the right of the aorta because the pulmonary artery is more accessible on that side. This may result in conduit compression and low cardiac output contributing to the increased early mortality. Improper positioning results in turbulence that accelerates pseudointimal peel formation (13,21). In the series of Bailey et al. (18), compression of the conduit between the sternum and the heart was the primary cause of early obstruction. Both strict attention to conduit placement and leaving the sternum open in the early postoperative period when necessary has been helpful in maintaining a low early mortality rate in complex transposition. More recent experience (17,19) with the cryopreserved homograft has been associated with a lower incidence of early conduit obstruction in complex transposition of the great arteries.

Surgical timing. The timing of definitive surgical repair is an important aspect of the treatment of conotruncal abnormalities. Early corrective repair is advocated by many to prevent the development of pulmonary hypertension secondary to a long-standing shunt or torrential pulmonary blood flow with a pulmonary to systemic flow ratio (Qp/Qs) >3:1. Prior palliative shunts and pulmonary hypertension have been directly related to increased operative mortality in patients undergoing conduit placement (16). Many advocate that corrective repair should be undertaken as early as 6 to 12 months after the placement of a shunt, whereas others (10) have suggested avoiding palliative shunts altogether and undertaking total correction when severe hypoxia or congestive failure occur but before the development of pulmonary hypertension. We propose a staged approach. A palliative shunt of correct size should be placed initially for those patients with inadequate pulmonary blood flow. In most cases, definitive repair should be undertaken at age 4 to 5 years before the child starts school. By this age the patient has gained sufficient size to allow use of a generously sized conduit that will not be rapidly outgrown. Performing the operation before the child starts school avoids interruption of the child's social development and education. Patients should be followed up closely after a palliative shunt and definitive repair should be undertaken earlier if signs of pulmonary hypertension, ventricular failure or worsening cyanosis occur.

This staged approach is appropriate for children with complex transposition, children with pulmonary atresia with ventricular septal defect and some patients with complex forms of tetralogy of Fallot. However, in patients with truncus arteriosus definitive repair should be undertaken in infancy; preliminary pulmonary artery banding is rarely indicated (22).

Late outcome. The long-term outcome of patients undergoing right ventricle to pulmonary artery conduit placement has steadily improved and is much more favorable than the natural history of these anomalies. Patients surviving surgical repair tend to have excellent clinical results, dependent mostly on their ventricular function. However, the long-term patency of the conduit is finite, resulting eventually in the need for conduit replacement in the majority of patients.

Although conduit replacement is generally well tolerated, the associated risk is equal to that of any mediastinal reoperation, with the added danger of injury to the conduit on making the sternotomy. In addition to a 7% operative mortality rate reported for reoperations, Schaff et al. (23) reported a 13% to 27% incidence rate of serious hemorrhage during sternal reentry. In our experience only one early death (4.8%) occurred in 21 reoperations for right ventricular to pulmonary artery conduit replacement. Careful preoperative evaluation including lateral chest radiography and the use of the oscillating saw are useful in avoiding injury to the conduit at reoperation (24).

A valve is necessary in most right ventricular to pulmonary artery conduits because elevated right-sided pressure results in pulmonary regurgitation and right heart failure when a nonvalved conduit is used. Bioprosthetic valved conduits tend to calcify and develop pseudointimal peel formation resulting in stenosis and eventual valve and conduit failure. In the Boston Children's Hospital experience (11,16) with the Dacron porcine-valved conduits, the replacement rate of valved conduit was 19% at 5 years, 39% at 7 years and 100% at 10 years. Our own data similarly demonstrate a 25% replacement rate at a mean follow-up interval of 7.5 years.

Our results suggest improved valve and conduit longevity with the cryopreserved homograft, which retains viable fibroblasts and endothelial cells, allowing for continued production of collagen and repair of the valve matrix and intima (25–28). Homografts have a more favorable patency profile and are easier to implant than is the standard Dacron porcine-valved conduit. A cryopreserved homograft valve lifespan of 22 years has been obtained in the aortic position (29) and a lifespan >15 to 20 years should be possible for homograft conduits. The homograft is probably the most suitable extracardiac conduit in terms of its ease of handling, natural hemostatic properties and long-term durability and patency. However, availability continues to be a problem.

Conclusions. The introduction of the valved conduit has greatly facilitated the surgical repair of many congenital cardiac lesions that were previously uncorrectable and amenable only to palliative repair. The overall mortality rate for

these defects has decreased markedly since the introduction of the valved conduit. The cryopreserved homograft is technically easier to use and hence is able to be placed in a more favorable position, avoiding sternal compression and kinking. Avoidance of bleeding from stitches with the homograft may result in a decreased incidence of postoperative bleeding and tamponade. The importance of continued cell viability for conduit and valve longevity makes the homograft, with current methods of cryopreservation, the preferred right ventricle to pulmonary artery conduit. Reduced early mortality and improved long-term patency and function are possible with the antibiotic-sterilized, nutrient-preserved fresh or fresh-frozen homograft.

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